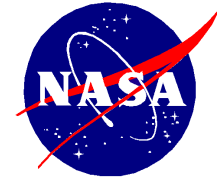




Entry Systems & Technology Division



Ablator Modeling: Why Not Much Has Changed Over the Past 45+ Years

B. Laub

NASA Ames Research Center
Moffett Field, CA 94035

Presented at
4th AF/SNL/NASA Ablation Workshop
Albuquerque, NM

1 March 2011



Outline



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

- Chronology
 - Early approaches to ablation modeling
 - Adoption of industry standard
- Constraints to further development
 - Not many new materials
 - Benefits vs. costs
- Modeling Enhancements
 - Addressing specific issues
- What's the payoff?



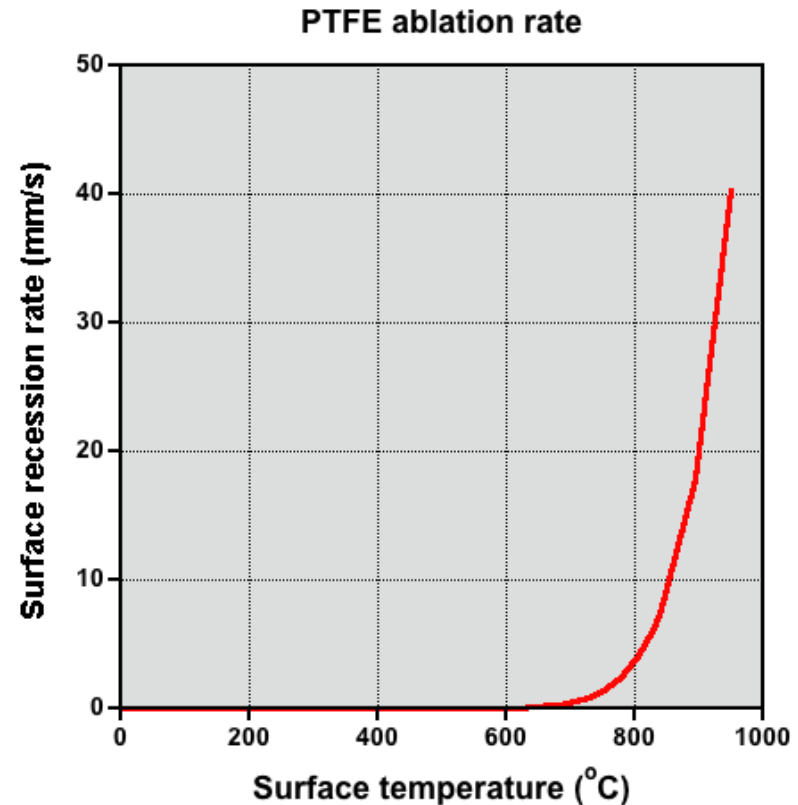
Early models



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

- Because teflon ablates over a very narrow surface temperature range, early models (late 50s-early 60s) were *constrained* by the concept of an “ablation temperature”
- This led to the development of the “heat of ablation” concept which is poorly understood and typically misapplied
- The “heat of ablation” (Q^*), is often referred to as a material “property.” It is not a *property* – it is a **data correlation parameter** that is only valid at **steady-state ablation conditions**.





What is the Heat of Ablation?



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

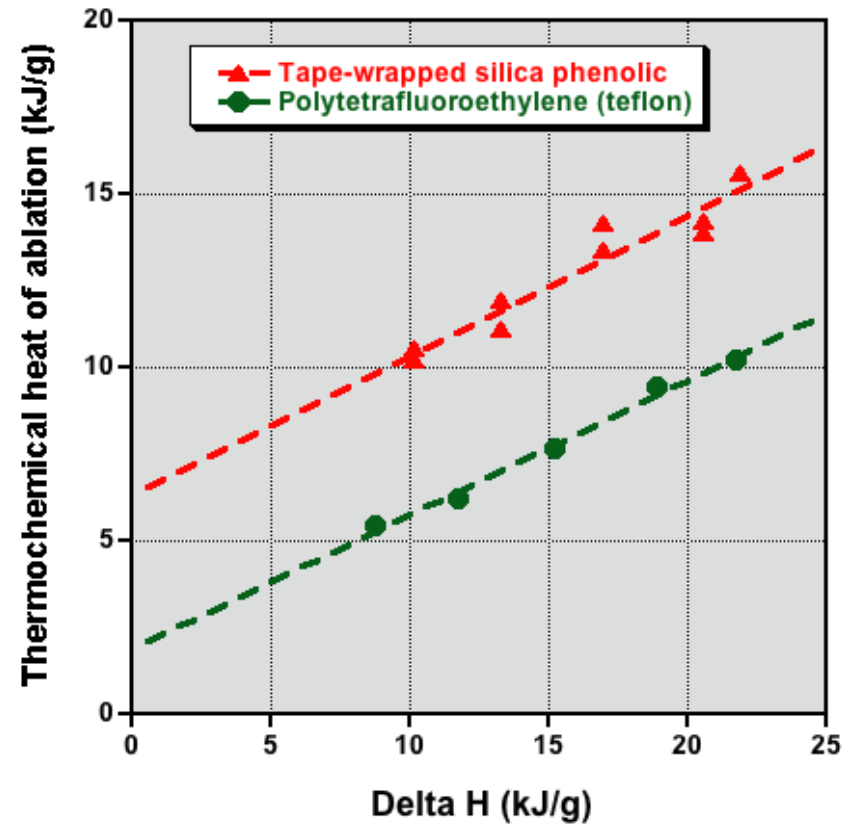
- The *thermochemical heat of ablation*, defined below, was calculated from the results of each arc jet test and plotted vs. $(H_r - H_{air}^{T_w})$

$$Q^* = \frac{\dot{q}_{cw} \left(\frac{H_r - H_{air}^{T_w}}{H_r} \right) - \sigma \epsilon T_w^4}{\rho \dot{s}} = c_p \Delta T + \Delta H_v + \eta \Delta H$$

A linear fit through the data produces a line whose slope is taken as η and whose y-intercept is taken as $c_p \Delta T + \Delta H_v$. Since c_p and ΔT are known or were determined in the test, one also derives ΔH_v from the linear fit of the data.

➤ Example:[†]

- Tape-wrapped silica phenolic ($\rho = 1.63 \text{ g/cm}^3$)
- PTFE ($\rho = 2.18 \text{ g/cm}^3$)
- Tests in Avco's Model 500 arc jet (circa 1965)
- Flat-faced stagnation samples in air
- Cold-wall heat fluxes in the range from $\approx 0.7\text{-}1.5 \text{ kW/cm}^2$



[†]"Ablation Handbook, Entry Materials Data and Design," AFML-TR-66-262, September 1966.



More Advanced Modeling



Entry Systems & Technology Division

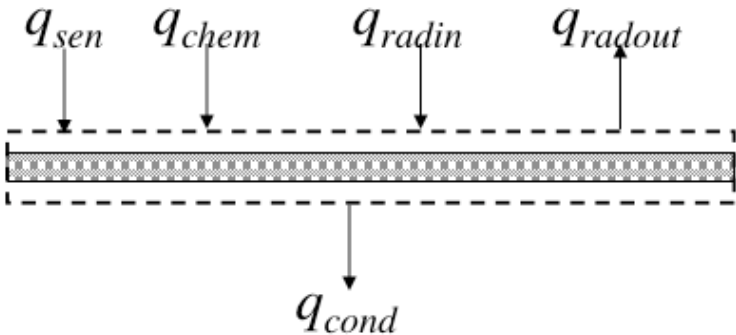
Entry Systems & Vehicle Development Branch

- Earliest model of in-depth thermal response for an organic resin composite was developed by Munson & Spindler¹ (Avco, 1962)
 - Included Arrhenius relation for decomposition kinetics
 - Surface recession primarily modeled via empirical correlation
- A more rigorous, chemical modeling approach was introduced by Kratsch, Hearne & McChesney² (Lockheed, 1963)
 - Modeled the composite as a mixture of organic resin and reinforcement (organic or inorganic), i.e.,

$$\rho_s = \Gamma \rho_{resin}(T, \theta) + (1 - \Gamma) \rho_{reinf}(T, \theta)$$

where Γ is the resin volume fraction.

- Kratsch, Hearne & McChesney adopted a transfer-coefficient approach (developed by Lees⁴) for approximating the heat transfer to an ablating surface from a chemically-reacting boundary layer



$$\underbrace{\rho_e u_e C_H (H_r - h_{ew})}_{q_{sen}} + \underbrace{\rho_e u_e C_M \left[\sum_i (Z_{ie}^* - Z_{iw}^*) h_i^{T_w} - B' h_w \right] + \dot{m}_c h_c + \dot{m}_g h_g}_{q_{chem}} + \underbrace{\alpha_w q_{rad}}_{q_{radin}} - \underbrace{F \sigma \epsilon T_w^4}_{q_{radout}} - q_{cond} = 0$$



Industry Standards



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

- Kendall, Rindal and Bartlett⁵ (Aerotherm, 1967) extended the work of Kratsch, Hearne & McChesney under contract to NASA JSC
 - One-dimensional thermal/ablation response of the charring ablator *fully coupled* to the non-similar, chemically reacting boundary layer (CABLE)
 - Bifurcation approximation for diffusion coefficients extended the formulation to cases of unequal diffusion coefficients and $Pr \neq Le \neq 1.0$
 - Corrected energy equation to account for energy associated with surface recession

$$\rho c_p \frac{\partial T}{\partial \theta} \bigg|_x = \frac{1}{A} \frac{\partial}{\partial x} \left(kA \frac{\partial T}{\partial x} \right)_{\theta} + \left(h_g - \bar{h} \right) \frac{\partial \rho}{\partial \theta} \bigg|_y \frac{\dot{m}_g}{A} \frac{\partial h_g}{\partial x} \bigg|_{\theta} + \dot{s} \rho c_p \frac{\partial T}{\partial x} \bigg|_{\theta}$$

- Under USAF sponsorship, separated CABLE into three standalone codes that became industry standards (1970)
 - **BLIMP**: Non-similar chemically-reacting boundary layer code
 - **CMA**: one-dimensional charring ablation code
 - **ACE**: chemical equilibrium code (treated open systems, i.e., produces thermochemical equilibrium solutions of B' for any chemical system (with limited capability to treat reaction-rate limited chemistry))



Constraints on Further Development



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

- Models for the ablative materials of interest were developed and *validated* in the late 60s-mid 70s
 - Not many new ablative materials being developed
 - NASA shifted attention to reusable TPS (Shuttle)
- TPS designs were successful
 - Further modeling improvements could potentially provide relatively small improvements in TPS mass
 - Data requirements to support such modeling advancements would require significant investment
- Cost-benefit analysis not favorable



Modeling Enhancements



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

- Since CMA was made widely available in 1970, there have been several modeling improvements developed within the industry, including:
 - FIAT – converted CMA's explicit pyrolysis logic to implicit and redesigned the code for TPS sizing
 - Several 1-D finite volume and finite element codes developed
 - 2-D (e.g., TITAN) and 3-D codes (e.g., TRAPS) developed (same basic modeling as CMA/FIAT)
 - Addition of transient momentum equation or D'Arcy Law (steady-state) to calculate in-depth pore pressure due to pyrolysis
 - Addition of models to predict char spall (thermal and pressure stresses)
 - Addition of models to predict particle impact erosion (empirically-based)
 - Addition of logic to calculate surface thermochemical ablation as part of thermal response (eliminates requirement for B' tables)
 - Recent efforts to couple thermal/ablation response to CFD (e.g., FIAT/DPLR)
 - Recent efforts to calculate pyrolysis gas chemistry with reaction kinetics



Current & Future Efforts



Entry Systems & Technology Division

Entry Systems & Vehicle Development Branch

- Significant interest in community to develop/introduce models for:
 - Pyrolysis gas and surface ablation chemistry governed by reaction kinetics
 - Surface catalysis
 - Coupling surface ablation chemistry with CFD
 - Surface roughness and mass injection effects
 - In-depth radiation transport
 - Others?
- Issues:
 - Acquiring the data necessary to support model development and validation requires sophisticated experiments and diagnostics
 - The number and availability of test facilities (e.g., arc jets) capable of simulating environments of interest is very limited
 - The potential for model validation with data from instrumented flight experiments is highly unlikely
- Acquiring the resources (\$\$\$) to support advanced model development will require a favorable cost-benefit demonstration